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The effects of spacing and thinning on stand and tree characteristics of 38-year-old Loblolly Pine

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Abstract

The effects of early and continuous density control on the characteristics of mature loblolly pine (*Pinus taeda* L.) were measured at age 38 and analyzed. Trees in plots planted at spacings of 1.8×1.8, 2.4×2.4, 2.7×2.7, 3.0×3.0, and 3.7×3.7 m were either left unthinned or thinned every 5 years beginning at age 18, to residual basal areas of 27.5, 23.0, 18.4, and 13.8 $m^2\ ha^{-1}$. Trees thinned from plot buffer zones at age 38 were selected to represent a final harvest cross-section of each treatment for evaluation of bole form, component biomass, and crown architecture. Volume and biomass of cut trees from all thinnings were included with the age 38 data for stand level yield comparisons. Results show thinning effects were generally more pronounced than spacing effects. Trees of the same diameter at breast height and total height from heavily thinned stands had more cylindrical lower boles, more upper stem taper, longer crowns with more and larger branches, more total foliage, and hence more biomass than trees from unthinned or lightly thinned stands. All levels of thinning increased the yield of the stand in terms of foliage and branch biomass, while only light or moderate thinning increased bole biomass and volume yields. The magnitude of these differences are presented.

Keywords: Loblolly pine (*Pinus taeda* L.); Spacing; Thinning; Taper; Volume; Biomass; Branches; Foliage; Crown architecture

1. Introduction

At ages between planting and end of rotation, loblolly pine (*Pinus taeda* L.) has likely been the most studied tree in the US. However, less is known about the tree's characteristics in older plantations because there are few older plantations available for study. Although several studies have described tree and stand growth and yield and tree form in planted and natural stands of different densities (e.g. USDA, Forest Service, 1929; Schumaker and Coile, 1960; Brender and Clutter, 1970; Mann and Dell, 1971; Baldwin and Feduccia, 1987; Burkhart et al., 1987), information regarding the morphology and yield differences in older plantations is lacking.

We analyzed standing-tree measurements and intensive felled-tree measurements (of thinned trees) at age 38 of a long-term, loblolly pine growth and yield study. Our objective was to show the effects of initial planting spacing and thinning (1) on biomass and volume

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yields, and stand structure, (2) on individual tree component biomass and volume yields, and bole form, (3) on the length, diameter, and quantity of branches and (4) foliage weight and its vertical distribution. Furthermore, we developed equations to predict the magnitude of the density effects on these variables.

An earlier paper (Bower and Baldwin, 1992) described the growth and yield trends within these stands from ages 18–38. Lumber and grade yields and wood quality results obtained from the felled trees in the age 38 thinning were published in Clark et al. (1994).

2. Procedures

2.1. Study plantation

The study plantation is located in southwest Louisiana on a cut-over longleaf pine (*P. palustris* Mill.) site near Merryville. Site preparation consisted of stump removal and burning. The 32 ha study site was machine- planted in January 1952 at spacings of 1.8×1.8 m (2990 stems ha^{-1}), 2.4×2.4 m (1683 stems ha^{-1}), 2.7×2.7 m (1329 stems ha^{-1}), 3.0×3.0 m (1077 stems ha^{-1}), and 3.7×3.7 m (746 stems ha^{-1}) in 20 strips 40.2 m wide by 402 m long.

At age 18, one half of the study was divided into 100, 40.2 by 40.2 m (.1619 ha) plots. Twelve of these were deemed unusable at the time. Thinning levels of no thinning and residual basal area (BA) densities of 13.8, 18.4, 23.0, and 27.5 $m^2\,ha^{-1}$ were installed at random within each spacing. Measurement plots were 0.0405 ha with a 10.1 m buffer surrounding each measurement plot. Each plot was thinned to its assigned BA at ages 18, 23, 28, 33, and 38. Thinning was from below with the exception that dominants were cut when they had broken tops, were severely forked, or diseased.

2.2. Sample trees

At age 38 trees were selected for thinning from the measurement plots using the same criteria as previous thinnings, but in the plot buffers, trees were randomly selected across the range of all diameters to achieve a representative sample of trees that would have been cut in a final harvest of the stand. These trees provided the information reported here, and for lumber and grade yields and wood quality (Clark et al., 1994). A total of 65 trees were thinned from the measurement plots and 242 trees from the plot buffers. Cut trees ranged from 22.9 to 44.2 cm diameter at breast height (DBH) and averaged 24.1 m total tree height (HT). The trees were felled with chainsaws and bucked into sawlogs 2.4–4.9 m in length. Estimates of volume and biomass of trees thinned from measurement plots prior to age 38 were included when calculating stand yield values.

One hundred and eight of the cut trees (12 from each of the 1.8×1.8, 2.7×2.7, 3.7×3.7 m spacings and the unthinned, 13.8, and 23.0 $m^2\,ha^{-1}$ thinning combinations) were measured in detail after felling. The plots selected for this subset of treatment combinations were chosen at random from the original blocks. Seventy-five of the sample trees were dominants, 23 were codominants, and 10 were intermediates. Outside-bark (ob) bole diameter measurements were made from the base of the stump to the tree tip at about 0.61 meter intervals. Inside-bark (ib) diameter measurements were obtained from disks cut at each 4.9 or 2.4 m log length from the base of the stump to the minimum merchantable diameter. Total height was re-measured, as well as height to base of live crown (HBLC), height to each branch (BRHT, dead or alive), and the basal diameter of each branch (BRDIA). The crown was divided into vertical one-thirds and one live branch was randomly sampled from each vertical section. Branch length, weight, and branch foliage weights were measured and used to determine the biomass of the entire tree and its components according to the procedures of Baldwin (1987).

2.3. Data analysis

Stand-level yield comparisons were conducted on all treatment combinations, except for the widest spacing and the lightest thinning, which never achieved target basal area. Equations to predict biomass and volume for the stand yields came from Baldwin and Feduccia (1987). The three-parameter Weibull function (Weibull, 1951; Bailey and Dell, 1973) was fitted to the plot diameter data using the maximum-likelihood procedure. The General Linear Models Procedure of the Statistical Analysis System (SAS Institute, 1988) was used for the analysis of variance (ANOVA). The (ANOVA) summary table for each stand variable tested was:

Source	*Degrees of freedom*
Spacing	4
Thinning	4
Block	2
Spacing×thinning	15
Error	62
Total	87

Individual treatment comparisons were estimated using the Tukey–Kramer procedure (SAS Institute, 1988).

Comparisons of tree characteristics included only the three spacings and three thinning treatment combinations of the 108 sample trees. Comparisons were done using ANOVA with current number of trees surviving, basal area per unit area, their interaction, and blocking as independent variables. The ANOVA summary table for each variable tested was:

Source	*Degrees of freedom*
Spacing	2
Thinning	2
Block	2
Spacing×thinning	4
Error	97
Total	107

The ANOVA comparisons served to point out the specific treatment differences.

The two-parameter Weibull distribution was used to model the vertical distribution of the foliage biomass (Schreuder and Swank, 1974; Vose, 1988) according to the procedures explained in Baldwin et al. (1993). Comparisons of inside-bark bole taper and form were done by comparing taper functions (Wensel and Krumland, 1983; Baldwin and Feduccia, 1991). The taper functions were fit to the sample tree data for each thinning and spacing treatment, for the unthinned plot data by spacing, and to all sample tree data combined. Recently developed loblolly pine crown shape equations (Baldwin and Peterson, 1997) were utilized to illustrate treatment effects on the predicted crown shape of a tree within each of the three spacing and thinning treatments.

Regression equations to predict crown characteristics were developed using the tree and stand variables that provided the best fit. An allometric model of the following form was used for the equations:

$$\ln Y = b_0 + b_1 \ln x_1 + b_2 \ln x_2 + \cdots + b_n \ln x_n \qquad (1)$$

3. Results

Tables 1–4 contain means from the ANOVA analyses. These tables show specific means of the variables for each spacing-thinning combination so the reader can observe any thinning intensity trend within a spacing, or vice versa. Since spacing-thinning treatment sample sizes were not always equal, stand level means and analyses (Tables 1 and 2) were weighted by the size of the plot.

3.1. Stand level

Number of trees planted per unit area (NTP), which varied according to the spacings selected, and residual basal area, which varied according to the thinning levels selected, were the experimental control (treatment) variables. NTP varied from 827 to 2894 stems ha^{-1} for the five spacing treatments and averaged 1584 stems ha^{-1} across the thinning treatments. The mean residual BA across all treatment combinations ranged from 15.9 to 36.1 $m^2\,ha^{-1}$ at age 38. Although BA was significantly different (P=0.0089) for the two widest spacings, the greatest difference occurred in thinned versus unthinned stands–the maximum difference between any of the spacing treatments was only 3.5 $m^2\,ha^{-1}$. The average number of trees surviving per hectare (TS) across all treatments at age 38 was 375 with a range of 146–817 (Table 1). Trees surviving was significantly affected by spacing and thinning treatments at P=0.0001 and was generally as one would expect: the wider the spacing or more intense the thinning, the lower the TS (Table 1).

The treatment effects on the quadratic mean diameter (QMD) were significant for both spacing and thinning treatments at P=0.0001. Quadratic mean diameter was inversely proportional to both initial planting density and thinning intensity. The largest diameter trees were produced by the widest spacing

Table 1
Treatment means of stand characteristics and parameters for a three-parameter Weibull function describing the diameter distribution of 38-year-old planted loblolly pine

Spacing (m)	Variable	Residual basal area after thinning (m^2 ha^{-1})				
		Unthinned	27.5	23.0	18.4	13.8
1.8×1.8	Trees surviving (No ha^{-1})	817	602	472	343	215
	Basal area (m^2 ha^{-1})	31.0	29.6	26.0	21.3	16.2
	Bole volume (m^3 ha^{-1})	338.9	474.4	461.9	413.0	390.3
	Quadratic mean diameter (cm)	22.0	25.5	26.7	28.5	31.4
	Weibull A parameter	3.4	5.3	6.6	8.8	9.2
	Weibull B parameter	5.6	5.0	4.2	2.6	3.3
	Weibull C parameter	3.2	3.0	2.6	2.0	3.1
2.4×2.4	Trees surviving (No ha^{-1})	770	568	399	313	199
	Basal area (m^2 ha^{-1})	36.1	31.3	26.0	21.0	17.2
	Bole volume (m^3 ha^{-1})	409.5	481.6	467.9	381.4	400.3
	QMD (cm)	24.5	26.6	28.8	30.1	33.5
	Weibull A parameter	5.4	5.2	8.8	8.5	10.0
	Weibull B parameter	4.5	5.6	2.7	3.5	3.3
	Weibull C parameter	2.1	3.6	1.5	2.0	2.4
2.7×2.7	Trees surviving (No ha^{-1})	652	414	355	290	178
	Basal area (m^2 ha^{-1})	35.2	28.7	24.8	21.2	17.1
	Bole volume (m^3 ha^{-1})	417.0	500.9	431.3	363.4	386.1
	QMD (cm)	26.1	29.9	30.6	30.8	35.1
	Weibull A parameter	4.6	8.7	9.2	9.6	5.9
	Weibull B parameter	6.1	3.3	3.0	2.7	8.2
	Weibull C parameter	2.7	2.0	2.0	1.7	7.8
3.0×3.0	Trees surviving (No ha^{-1})	551	432	321	233	201
	Basal area (m^2 ha^{-1})	28.7	28.8	23.4	19.0	16.2
	Bole volume (m^3 ha^{-1})	321.4	406.8	380.2	367.7	321.4
	QMD (cm)	25.8	29.2	30.5	32.6	33.0
	Weibull A parameter	1.4	5.0	5.6	9.8	5.7
	Weibull B parameter	9.3	7.0	6.7	3.3	7.6
	Weibull C parameter	4.6	4.0	5.3	2.4	8.3
3.7×3.7	Trees surviving (No ha^{-1})	469	–	271	237	146
	Basal area (m^2 ha^{-1})	32.8	–	26.0	20.1	15.9
	Bole volume (m^3 ha^{-1})	403.6	–	435.3	347.5	326.4
	QMD (cm)	29.9	–	35.2	33.3	37.5
	Weibull A parameter	3.8	–	7.8	10.3	8.3
	Weibull B parameter	8.3	–	6.2	2.9	6.5
	Weibull C parameter	4.5	–	4.9	1.8	3.2

and the heaviest thinning combination (37.5 cm in the 3.7×3.7 m–13.8 m^2 ha^{-1} treatment combination).

The effect of thinning on diameter distribution is shown in Fig. 1. Increasing the intensity of thinning shifted the distribution to the right and narrowed the range of diameters. This is reflected in the significant changes in the '*a*' parameter (P=0.0001) and the '*b*' parameter (P=0.0043) (those parameters that control the scale of the distribution). Only the heaviest thinning treatment did not reflect the trend of a gradually increasing '*a*' parameter value and gradually decreasing '*b*' parameter value (Table 1). Thinning intensity did not affect the shape of the diameter distribution – differences in the '*c*' parameter were nonsignificant (P=0.1861) (the parameter that controls the shape of the distribution). There was no discernible trend in any of the distribution parameters due to spacing effects at age 38, although the '*b*' parameter differences were statistically significant (P=0.0314).

Table 2
Treatment means of stand characteristics of 38-year-old planted loblolly pine

Spacing (m)	Variable	Residual basal area after thinning (m^2 ha^{-1})				
		Unthinned	27.5	23.0	18.4	13.8
1.8×1.8	Dominant height (m)	23.0	24.4	25.2	23.7	24.3
	Height (m)	21.1	23.4	24.3	23.3	24.2
	Bole biomass (Mg ha^{-1})	151.5	209.0	203.1	177.2	165.2
	Foliage biomass (Mg ha^{-1})	6.3	13.2	14.0	16.4	15.9
	Branch biomass (Mg ha^{-1})	13.0	22.5	23.2	25.7	25.7
	Crown mass/tree mass	0.11	0.11	0.11	0.13	0.13
2.4×2.4	Dominant height (m)	23.8	25.0	24.9	24.0	24.5
	Height (m)	22.6	24.2	24.4	23.5	24.5
	Bole biomass (Mg ha^{-1})	185.0	215.3	206.1	165.1	169.9
	Foliage biomass (Mg ha^{-1})	7.4	10.9	12.8	12.8	15.7
	Branch biomass (Mg ha^{-1})	16.3	20.8	24.0	23.0	27.5
	Crown mass/tree mass	0.11	0.11	0.12	0.13	0.14
2.7×2.7	Dominant height (m)	24.9	25.8	25.5	23.5	25.1
	Height (m)	23.5	25.5	25.1	23.2	25.0
	Bole biomass (Mg ha^{-1})	190.0	224.8	191.1	157.4	165.2
	Foliage biomass (Mg ha^{-1})	7.3	11.1	10.9	12.0	14.1
	Branch biomass (Mg ha^{-1})	16.8	22.7	21.8	22.6	26.0
	Crown mass/tree mass	0.11	0.11	0.12	0.14	0.14
3.0×3.0	Dominant height (m)	23.2	24.5	24.4	23.9	23.6
	Height (m)	21.9	23.9	23.6	23.6	23.4
	Bole biomass (Mg ha^{-1})	144.9	182.6	167.5	158.7	137.7
	Foliage biomass (Mg ha^{-1})	6.4	8.9	10.3	11.9	11.4
	Branch biomass (Mg ha^{-1})	14.3	19.3	21.0	23.5	21.8
	Crown mass/tree mass	0.13	0.12	0.13	0.14	0.15
3.7×3.7	Dominant height (m)	26.0	–	26.6	23.6	24.9
	Height (m)	25.1	–	26.1	23.5	24.8
	Bole biomass (Mg ha^{-1})	186.0	–	196.7	151.8	142.0
	Foliage biomass (Mg ha^{-1})	6.9	–	9.3	10.2	9.8
	Branch biomass (Mg ha^{-1})	17.0	–	22.4	21.8	21.9
	Crown mass/tree mass	0.11	–	0.13	0.15	0.15

The thinning treatments clearly affected total bole volume and biomass (P=0.0001). Bole volume and biomass increased dramatically from unthinned to the lightest thinning treatments, and then gradually decreased as thinning intensity increased. Bole volume and biomass differences due to planting spacing, although statistically significant (P=0.0002 and 0.0005, respectively), were relatively small with no trend (Tables 1 and 2). The mean yield for all spacings was 397 m^3 ha^{-1} for bole volume and 174 Mg ha^{-1} for bole biomass. The largest mean differences occurred between the 2.4×2.4 and 3.0×3.0 m spacings (72.8 m^3 ha^{-1} and 31.9 Mg ha^{-1} for volume and biomass, respectively). The highest total bole volume and biomass due to spacing were achieved with the 2.4×2.4 m spacing, and the highest due to thinning were achieved with the 27.5 m^2 ha^{-1}thinning treatment.

Spacing and thinning treatments affected mean height[1] of all the trees and mean height of the dominants and codominants, although the differences were inconsistent with respect to treatment levels. The greatest treatment difference was about 5 m (Table 2). Since many of the heights were predictions, no

[1] Some standing tree height measurements taken at age 38 were with a faulty instrument. Fortunately, many of the tree measurements were made with a separate accurate instrument. The good measurements were combined with the felled tree measurements to develop an equation to predict total height of the remaining trees. Thus, height statistics are based on both measured and predicted values.

Table 3
Treatments means of individual tree crown component characteristics for 38-year-old planted loblolly pine

Spacing (m)	Variable	Residual basal area after thinning (m^2 ha^{-1})		
		Unthinned	23.0	13.8
1.8×1.8	Branch diameter (cm)	2.5	3.1	3.9
	Maximum branch diameter (cm)	5.4	6.3	7.6
	Branch length (m)	1.7	2.1	2.6
	Maximum branch length (m)	3.6	4.3	5.0
	Branch biomass (kg)	16.4	38.1	69.0
	Foliage biomass (kg)	7.5	16.7	25.5
2.7×2.7	Branch diameter (cm)	2.6	3.2	3.6
	Maximum branch Diameter (cm)	5.2	6.3	6.8
	Branch length (m)	1.8	2.1	2.5
	Maximum branch length (m)	3.6	4.3	4.7
	Branch biomass (kg)	16.9	36.8	60.3
	Foliage biomass (kg)	7.8	14.6	21.2
3.7×3.7	Branch diameter (cm)	2.9	3.3	3.9
	Maximum branch Diameter (cm)	5.6	8.1	8.0
	Branch length (m)	2.0	2.2	2.6
	Maximum branch length (m)	3.8	5.2	5.3
	Branch biomass (kg)	31.6	41.0	86.2
	Foliage biomass (kg)	14.6	13.7	26.4

Table 4
Treatments means of individual tree component characteristics and parameters for a two-parameter Weibull function describing the vertical foliage distribution for 38-year-old planted loblolly pine

Spacing (m)	Variable	Residual basal area after thinning (m^2 ha^{-1})		
		Unthinned	23.0	13.8
1.8×1.8	Branches (number)	31.1	38.5	38.1
	Crown mass/tree mass	0.09	0.12	0.16
	Crown length (m)	5.6	7.4	8.4
	Height to live crown (m)	17.5	17.6	16.9
	Weibull B parameter	4.0	5.0	5.4
	Weibull C parameter	2.7	2.6	2.7
2.7×2.7	Branches (number)	29.7	35.8	41.7
	Crown mass/tree mass	0.07	0.12	0.15
	Crown length (m)	6.0	6.5	8.8
	Height to live crown (m)	18.8	18.3	15.9
	Weibull B parameter	4.1	4.8	5.9
	Weibull C parameter	2.8	2.9	2.8
3.7×3.7	Branches (number)	34.3	31.1	45.0
	Crown mass/tree mass	0.09	0.11	0.16
	Crown length (m)	6.8	6.7	9.0
	Height to live crown (m)	18.9	17.8	16.3
	Weibull B parameter	4.6	4.8	5.8
	Weibull C parameter	2.7	2.9	2.6

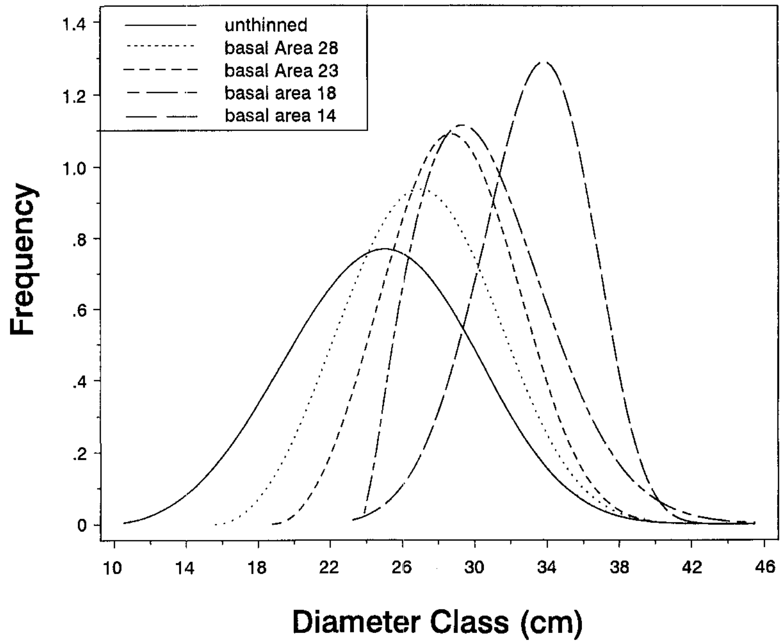

Fig. 1. Mean diameter distributions of age 38 plantation loblolly pine for each of five thinning treatments as modeled with the Weibull function.

statistical inferences directly involving tree height are presented. The 23 and 27.5 $m^2 ha^{-1}$ thinning levels produced the tallest dominant and codominant trees across all spacings, and the wider spacings generally produced the tallest dominant and codominant trees across the thinning treatments. The 3.7×3.7 m–23.0 $m^2 ha^{-1}$ spacing-thinning combination produced the tallest trees in the study (26.1 m).

Stand foliage and branch biomass yields were affected by thinning (Table 2, P=0.0001). As in bole biomass, foliage and branch biomass yields significantly increased when stands were thinned, but continued to increase or remain relatively constant as thinning intensity increased. There were no evident trends across the spacing treatments for either foliage or branch biomass, and foliage biomass alone was statistically significant (P=0.0001) for the spacing treatments. Foliage and branch biomass averaged 11.2 Mg ha^{-1} and 21.6 Mg ha^{-1}, respectively, across the spacing treatments. The 2.4×2.4 m–13.8 $m^2 ha^{-1}$ combination produced the heaviest crowns (branches plus foliage) on a stand basis (43.2 Mg ha^{-1}).

At age 38, 5 years after the most recent thinning, the proportion of crown biomass to total above-ground biomass of the trees ranged between 0.11 and 0.15 regardless of the spacing or thinning level. Though the differences were small, both spacing and thinning treatments were significant (P=0.0001). Higher proportions were in stands with wider spacings and heavier thinnings.

3.2. Tree level

Heavier thinning significantly increased (P=0.0001) both foliage and branch biomass of individual trees (Table 3). However, planting spacing effects on branch biomass were significant only for the 3.7 m spacing, while foliage biomass had no significant differences (p=0.1212) or consistent trends. Heavier thinning significantly increased the number of branches per tree (P=0.0001) (Table 4), mean (P=0.0001) and maximum (P=0.0001) branch diameter, and mean (P=0.0001) and maximum (P=0.0001) branch length (Table 3). For example, the heaviest, as compared to the lightest thinning, produced trees with 31% more branches that were 43% longer and 42% larger in diameter. Planting spacing also influenced the maximum branch diameter (Table 4) (P=0.0431), but had no significant effect on the number of branches (P=0.7293), mean branch diameter (P=0.1313), mean branch length (P=0.2177), or maximum branch length (P= 0.1028)(Table 3). Trends for all of these variables across the thinning treatments were obvious, but generally inconsistent for the spacing treatments (Tables 3 and 4).

Crown length was significantly longer as thinning intensity increased (P=0.0001). This was mainly due to a slower crown rise (HBLC) in the less dense stands. This observation was also reflected in significantly different (P=0.0001) and consistently larger ratios of crown biomass to total above-ground tree biomass (Table 4) as thinning intensity increased. No consistent trends nor significant differences between any of these variables was noted due to differences in planting spacing.

Table 4 shows the thinning and spacing effects on the vertical distribution of crown foliage weight using the two-parameter Weibull function. As in the three-parameter Weibull, the 'b' parameter controls the scale and the 'c' parameter controls the shape of the distribution. The 'b' parameter changed due to both spacing and thinning, but only the thinning effect was statistically significant (P=0.3313 spacing, P=0.0001 thinning). The parameter value increased as thinning intensity increased. There were neither trends nor significant differences in the 'c' parameter due to the treatments (P=0.1736 spacing, P=0.4595 thinning).

The resulting equations for prediction of number of branches, mean and maximum branch diameter and length, and total branch and foliage weight accounted for 44–82% of the variability in predicting these branch and foliage characteristics.

The treatment effects on crown length and overall crown shape are visually summarized in Figs. 2 and 3 where predicted crown shapes (Baldwin and Peterson,

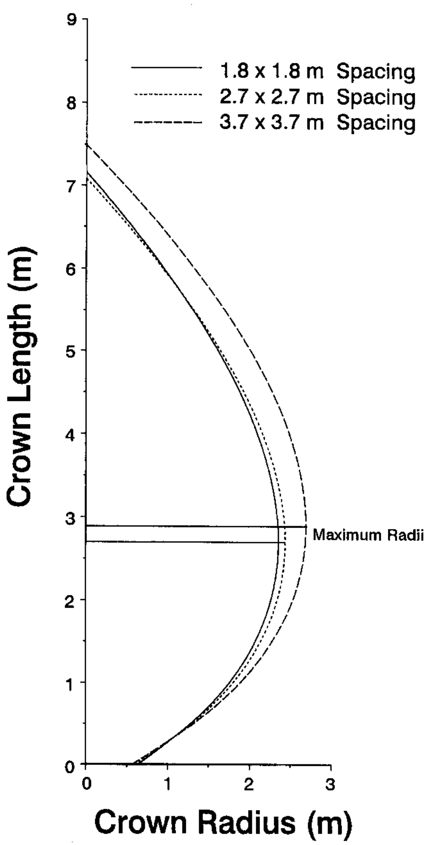

Fig. 2. Mean profile of the crown shape of age 38 plantation loblolly pines as influenced by three planting spacings.

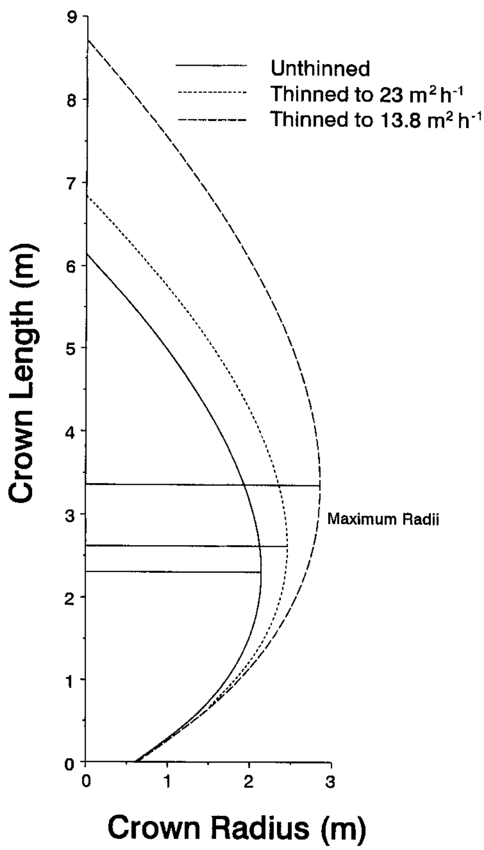

Fig. 3. Mean profile of the crown shape of age 38 plantation loblolly pines as influenced by three thinning-level treatments.

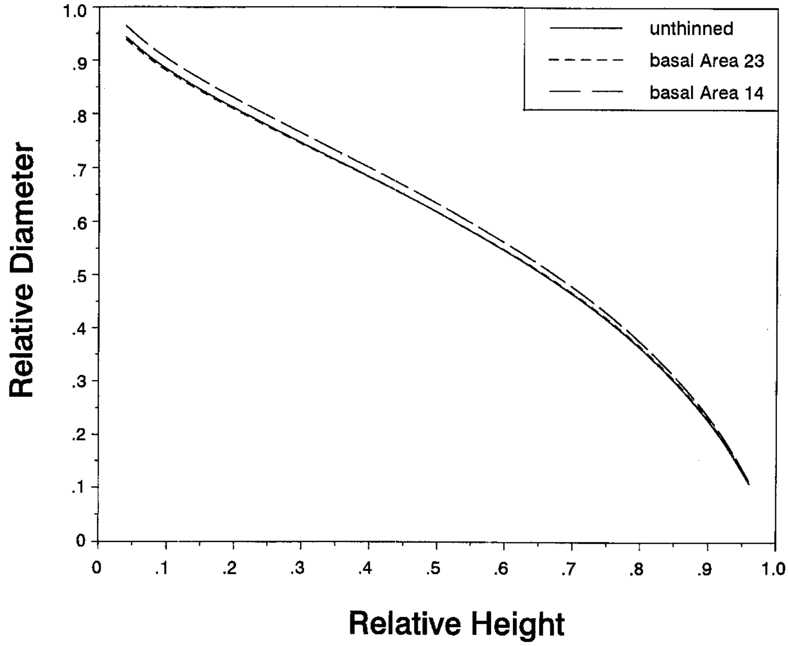

Fig. 4. Mean profiles of three typical age 38 planted loblolly pines each showing the influence of stand thinning intensity on residual tree stem form.

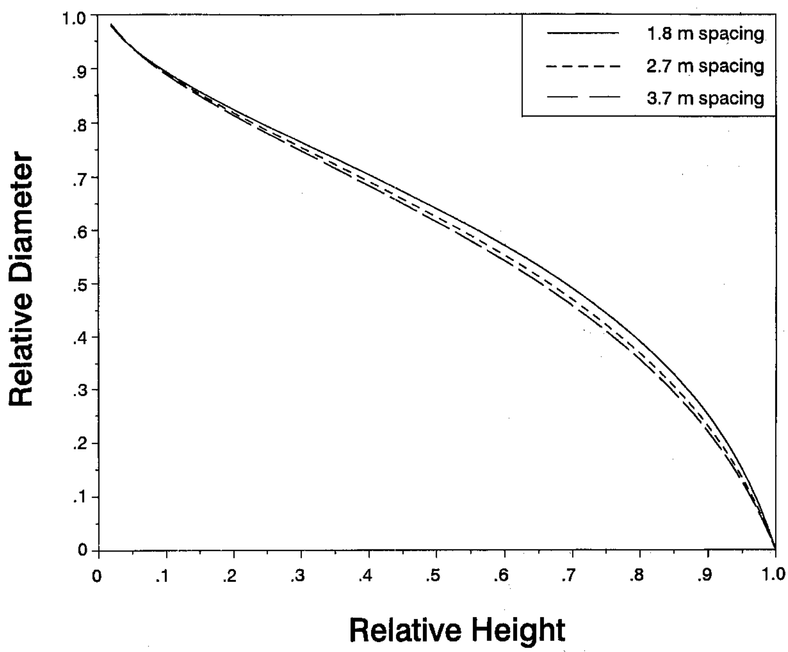

Fig. 5. Mean profiles of three typical age 38 planted loblolly pines each showing the influence of a different initial planting spacing on residual tree stem form.

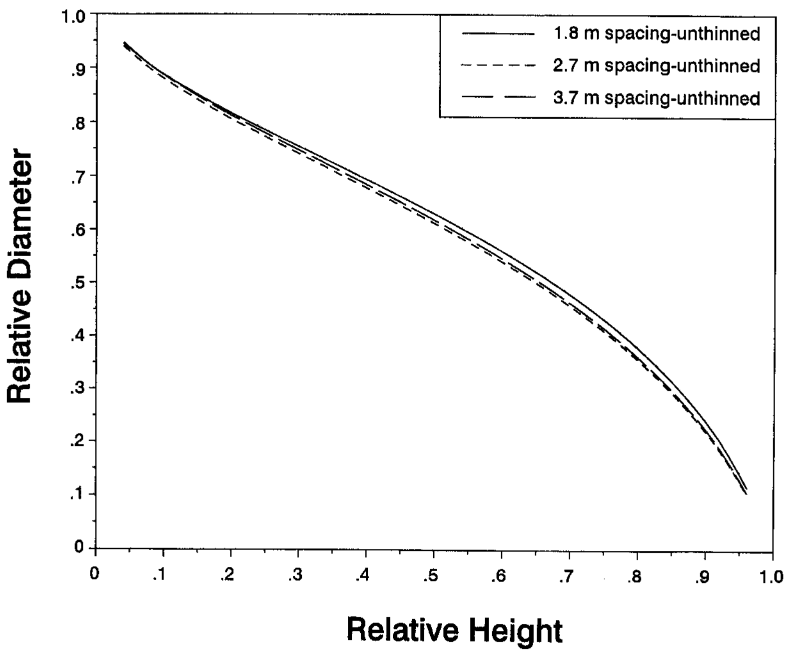

Fig. 6. Mean profiles of three typical age 38 planted loblolly pines each showing the influence of a different initial planting spacing on residual tree stem form in stands that were never thinned.

1997) for an average tree within each of the three spacing treatments and each of the thinning treatments, respectively, are presented. As stand density decreased, crown length, width, and hence volume, became greater. At age 38, in stands that were thinned and spaced to different levels, the thinning effect was the most pronounced.

The tests for differences between fitted taper functions for the thinning and spacing levels indicated there were significant differences between the parameters for all the functions (P=0.0001). However, thinning and spacing effects on tree taper were opposite. Using individual tree volume predictions to illustrate this phenomenon, total volume of a tree of the same DBH and HT was greater in more heavily thinned stands than in unthinned or lightly thinned stands, but total volume was less in more widely spaced stands than in more closely spaced stands (Figs. 4 and 5). With respect to the spacing trend, the same result was observed (Fig. 6) in trees from plots that were never thinned, indicating this phenomenon was not a spacing-thinning interaction effect.

4. Discussion and conclusions

The thinning treatments noticeably affected stand and tree characteristics for all spacings. However, age 38 values and trends were much less pronounced or null across the planting spacing treatments, except for QMD and TS. The result was similar for volume and biomass yields across all spacings (only the size and number of trees varied). Analysis of unthinned plots yielded the same result; only TS, QMD, mean height of the dominants and co-dominants, and mean height of all trees were significantly affected by spacing treatments. Thus, an 'across-the-board' net fiber amount was maintained in the unthinned plots for each planting spacing by age 38.

Reaching the same yield production asymptote in evenaged stands of different densities has been reported and discussed by others (Kramer and Kozlowski, 1960; Borders, 1984; Smith, 1986) in the context of either initial stand spacing or thinning. Although not a universal phenomenon, we show it was obtained in stands of varying initial densities for unthinned plots. Yield definitely increased when plots were thinned, although it did decline as thinning intensity increased. Despite including volume and biomass from all thinnings when comparing stand yields at age 38, stands thinned at the most intense levels could not recover enough to maintain the same yield production asymptote in this study. There is insufficient evidence to state that biomass production, and yield, in stands of varying densities will stabilize through time. Smith (1986) suggested, and Borders (1984) showed for loblolly and slash pine (*Pinus elliottii* Engelm. Var. *elliottii*), that site quality and age are key factors that must be considered in determining if and when an upper yield asymptote is indeed achieved.

A biological factor often considered in selecting an optimum planting spacing or thinning level is the potential occupancy of the residual trees on a site. Too many trees over-utilize site resources, too few under-utilize the site. One measure of site occupancy is Stand Density Index[2] (SDI) developed by Reineke (1933). Mean SDI at age 38 was calculated from the mean TS and QMD (inches) values (Table 1) for each spacing and thinning combination. The SDI values for all treatment combinations ranged from 121 to 261. For loblolly pine in central Louisiana, a SDI of 450 is considered the maximum threshold (Dean and Baldwin, 1993) above which competition causes mortality. Dean and Baldwin (1993) suggest that when a stand reaches a density corresponding to 45% of maximum SDI (202) it will begin to experience significant intraspecific competition. In our study only the two closest spacings and two lightest thinning treatments exceeded SDI=202 at age 38, the mid-level spacings and thinnings were at that level, and the wider spacings and thinnings were below that level. Thus, the more open stands were not fully utilizing site resources, and none of the stands were experiencing heavy intraspecific competition at age 38.

As noted earlier, the amount of foliage within the stands was affected by planting spacing and thinning. At the tree level, however, thinning alone significantly affected foliage biomass. The amount of foliage on individual trees increased dramatically in open stands due to thinning. This allowed the more heavily thinned stands to surpass the average foliage biomass achieved across the spacing treatments. The unthinned plots clearly had the least amount of foliage biomass per hectare than any other treatment, while the smallest planting spacing (most dense) had the greatest amount of foliage biomass per hectare.

More and larger branches are needed to support the increased amount of foliage produced by lower stand densities (Kramer and Kozlowski, 1960). As a result of more and larger branches, crown length and width, and hence weight and volume, were also increased. At age 38 the crown responses were less pronounced as a result of planting spacing, but clearly indicated due to thinning. Crown rise was slower in more heavily thinned stands indicating increased and prolonged utilization of solar radiation available for photosynthesis.

The effects of thinning on bole taper confirm earlier reports of these changes (e.g. Smith, 1986). The result is increased total stem volume for trees of the same HT and DBH, as shown in this study, and previously by Baldwin and Feduccia (1987). However, this volume effect may not hold true for density reduction due to wider planting spacing. In this study the opposite effect was observed for 38-year old loblolly pines individual tree volume for trees of the same HT and DBH was reduced in the widest spacing. We surmise the reason for this is that taper is greatest in the crown portion of a loblolly pine tree (Larson, 1963). Thus, given two trees of equal DBH and HT but different crown lengths, bole volume will be less in the tree with the longer crown. Since in general this study showed that, no matter what the thinning level, mean tree crown length was longer in the wider spacings compared to the closer spacings, then (as was found) bole volumes should also be less in the wider spacings. This information, coupled with the results concerning increased branch size and number in trees grown at wide spacings, shows that both wood quantity and quality can be adversely affected by management decisions to increase bole size by planting at wider spacings in order to avoid or reduce the costs of thinning when sawlog production is the objective (Clark et al., 1994).

[2] In terms of Standard International Units, SDI=0.00229 TS(QMD)$^{1.6}$.

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